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New binary parameters for the symbiotic recurrent nova T Coronae Borealis

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ABSTRACT

The amplitude of the ellipsoidal variability, the mass function, and the evolutionary limits on the component masses have been used to constrain the binary system parameters of T Coronae Borealis. Contrary to all previous studies, our analysis shows that the mass ratio of T CrB $q \equiv M_{\rm g}/M_{\rm h} \approx 0.6$ which implies a low mass binary system, with the stellar masses $M_{\rm g} \sim 0.7{\rm M}_\odot$ for the red giant and $M_{\rm h} \sim 1.2{\rm M}_\odot$ for the hot companion. This result strongly supports the thermonuclear runaway model for this recurrent nova, and solves all controversies about the nature of the hot component and the physical causes of its eruptions.

Key words: stars: individual (T Coronae Borealis) – stars: novae – stars: binaries: symbiotic.

1 INTRODUCTION

T Coronae Borealis is a recurrent nova which underwent major eruptions in 1866 and 1946. Its quiescent optical spectrum shows M–type absorption features with the additional H I, He I, He II, and [O III] emission lines, and Balmer jump (Kenyon 1986, and references therein). Such type of optical spectrum qualified T CrB to be classified as symbiotic system. Recent classifications based on the TiO bands in the red part of spectrum, indicate that the cool component is a normal M4 III giant (Kenyon & Fernandez–Castro 1987), while the nature of its hot companion remains controversial.

Sanford (1949), and later Kraft (1958) noted periodic radial velocity changes in the M giant's absorption features and the H I emission lines. Kraft refined Sanford's period estimate to 227.6 days, derived a total mass of the system of 5 $\rm M_\odot$, and a mass ratio of 1.4 with the giant being the more massive component. He also noticed that the M giant should fill its Roche lobe. In fact, the characteristic double bump visible in the *VRIJ* light curves of T CrB indicates that the giant is indeed tidally distorted (Bailey 1975; Lines, Lines & McFaul 1988; Yudin & Munari 1993). Although the observed amplitude of the light and radial velocity changes suggests a large orbital inclination (Kenyon & Garcia 1986, hereafter KG), the lack of eclipses in the UV continuum and emission lines observed with the IUE indicates that the system is not eclipsing (Selvelli, Cassatella & Gilmozzi 1992, hereafter SCG).

Recent analysis of new radial velocity data for the giant component in T CrB combined with Sanford's and Kraft's data resulted in a new orbital solution and confirmed previous estimates for the component masses (KG). The spectroscopic orbit suggests that T CrB is relatively massive symbiotic system, and in particular that the companion to the M giant has a mass exceeding the Chandrasekhar limit, and thus must be a main sequence star. This led Webbink et al. (1987, hereafter WLTO) and Canizzo & Kenyon (1992) to interpretation of the nova–like outbursts of T CrB in terms of transient phenomena in a non–stationary accretion disk around a main sequence star. Unfortunately, as remarked by SCG, the accretion model has some weighty difficulties when confronted with most observational data. In fact, the mass ratio $q = 1.3$ and the resulting companion mass above the Chandrasekhar limit are the main arguments in favor of the accretion model, while practically everything else is rather against.

SCG based on extended study of IUE spectra of T CrB demonstrated that the quiescent UV characteristics of the hot component, in particular "(1) the fact that the bulk of the luminosity is emitted in the UV range with little or no contribution to the optical; (2) the presence of strong He II and N V emission lines, suggesting temperatures of the order of 10^5 K; and (3) the rotational broadening of the high-excitation lines.", the X-ray detection, as well as the flickering in the optical light curve reported at several epochs, are incompatible with the presence of main-sequence accretor, while they find natural and physically plausible interpretation in terms of a white dwarf acceptor. They also discussed the spectral and photometric behavior of T CrB during the 1946 outburst, and concluded that "(1) the spectral evolu-

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Table 1. References to collected data.

No.	Reference	Bands
1	Yudin & Munari (1993)	*J*
2	Raikova & Antov (1986)	*U, B, V*
3	Lines et al. (1988)	*U, B, V*
4	Hric et al. (1991)	*U, B, V*
5	Skopal et al. (1992)	*U, B, V*
6	Hric et al. (1993)	*U, B, V*
7	Hric et al. (1994)	*U, B, V*
8	Skopal et al. (1995)	*U, B, V*

tion (...) has followed the same pattern generally observed in fast novae; (2) the photometric light curve has obeyed the same relation $M_V^{\rm max} - t_3$ followed by classical novae; (3) the luminosity at maximum was super-Eddington, a distinctive signature of a TNR (thermonuclear runaway) model." Finally, they derived the accretion rate during quiescence, $\dot{M}_{\rm acc} \sim 2.5 \times 10^{-8} {\rm M}_{\odot}\,{\rm yr}^{-1}$, which is exactly that required by the theory to produce a TNR every 80 years on a massive white dwarf.

Though the orbit of the M giant is now very well established still the orbit of the companion is based on seven H_β radial velocity measurements by Kraft (1958). The H I emission lines in T CrB are however broad, up to ~ 500 km s^{-1}, and affected by variable absorption, which makes any orbital solution much more uncertain than the formal errors quoted by Kraft may suggest (see SCG and Warner 1995, for more detailed discussion). Moreover, recent studies of the H I emission line behavior in T CrB have demonstrated that the H I lines do not follow the orbital motion of any of the binary components (Anupama 1997; Mikołajewski, Tomov & Kolev 1997). The mass ratio, $q = 1.3$, derived by KG from analysis of the ellipsoidal variations in the radial velocity of the giant does not support Kraft's result, because the authors made errors in their Eq.(5) (see Sec. 3.4 for details). Thus the main argument in favor of the accretion model of T CrB outbursts does not hold any longer.

The aim of this work was to reexamine the binary model of T CrB basing on analysis of light curves and spectroscopic information. In particular, the ellipsoidal variability, the M giant mass function, and the $V \sin i$ allow us to constrain the binary parameters and to demonstrate that the system consists of a low mass M4 giant, $M_{\rm g} \sim 0.7 {\rm M}_{\odot}$, filling its Roche lobe, and a $\sim 1.2 {\rm M}_{\odot}$ companion most likely a white dwarf. Our results thus support SCG's interpretation of T CrB.

We describe our database in Sec. 2, analyze the data and discuss the results in Sec. 3, and conclude with a brief summary in Sec. 4.

2 OBSERVATIONAL DATA

We have collected all published photoelectric photometry of T CrB at quiescent phase. For the purpose of the present study we have however chosen only the measurements transformed to the standard Johnson's (1966) system. References to our database are listed in Table 1, the light curves are shown in Figure 1.

The V and J light curves are dominated by sinusoidal variation with half the orbital period, and the minima at times of spectroscopic conjunctions are caused by orbital motion of the tidally distorted red giant. Although this effect is also visible in the B light, it is superposed upon secular changes, and thus less pronounced. The U light curve is dominated by these secular changes, as well as some erratic and perhaps quasi–periodic variations which can be attributed to the hot component.

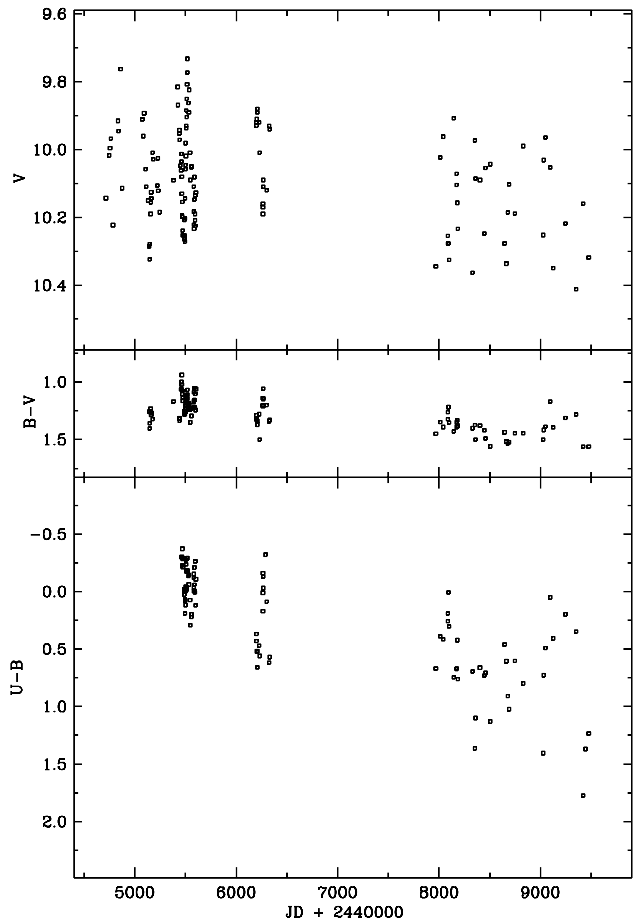

Figure 1. The UBV photometry of T CrB in 1981–94.

3 ANALYSIS

3.1 Variability

The ellipsoidal variability of T CrB was first demonstrated by Bailey (1975). Bailey also noticed that for the binary parameters, $q = 1.4, i = 68^\circ$ (Kraft 1958; Paczyński 1965a), the observed visual amplitude requires a very high value of the gravity–darkening coefficient $\alpha \gtrsim 1$. Lines et al. (1988) derived the amplitude of the ellipticity effect at $UBVRI$ by Fourier analysis, and used it to find the prolateness coefficient. They did not however attempt to refine the parameters of T CrB.

Lines et al. also found additional ~ 55 day variation with variable amplitude which they attributed to semiregular pulsations of the red giant, and suggested that the giant cannot be exactly filling its Roche lobe at all times. Their interpretation seems however implausible. First, the amplitude of the ~ 55 day variation is increasing towards shorter wavelengths, while the M giants pulsations have the largest amplitude in V light owing to presence of strong TiO bands

in this spectral range, which is manifested as *redder* $U-B$ and $B-V$ colors at maxima than at minima – just opposite to the behavior observed in T CrB. Second, the $U-V \sim 1.1$ observed in 1983, when the variation had the largest amplitude, is much lower than $U-V \sim 3.4$ expected for M3–4 III giants (Straizys 1992) which suggest very low contribution of the M giant to the U light. Finally, the V amplitude of this additional variability was largest in 1983 when the hot component was bright in the optical range as indicated by flickering observed in B and V light (Lines et al. 1988). All this points to the hot component as the source of ~ 55 day variation, although its origin is not clear.

Yudin & Munari (1993) published J light curve of T CrB based on 5.8 orbital cycles, and did not find any evidence for the M giant changing its intrinsic brightness by more than a few hundredths of magnitude. Their results provides additional strong support that the erratic and quasi–periodic large amplitude variations reported in the optical must be related to the M giant's companion.

The secular trends in the light curve of T CrB have been recently studied by Leibowitz, Ofek & Mattei (1996). Using amateur astronomers' visual observations spanning a period of nearly 40 years, they found a quasi–periodic, ~ 27 yr, oscillation superposed on a linear fading with an average rate of $\sim 10^{-5}$ mag/day. The interval covered by their data sample is however only 50% longer than the estimated period, which combined with rather large uncertainties in the visual magnitude estimates by various observers makes that result debatable.

Nevertheless, the occurrence of high and low luminosity states of the hot component is also suggested by the IUE observations (SCG), and optical emission line behavior (Anupama 1997; Mikołajewski et al. 1997). ¿From the data in Figure 1 we estimate the magnitude decrease of ~ 0.09 mag in V, ~ 0.24 mag in B, and ~ 1.1 mag in U, respectively, during the 1981–1994 period. The IUE observations reported by SCG also suggest that the hot component was apparently in much higher luminosity state in 1981–85 than in the 1990's. In 1996, the hot component regained the brightness level from early 1980's (Hric et al. 1997; Mikołajewski et al. 1997).

In our analysis we will focus on the V and J light curves where the M giant provides the dominant contribution, and the ellipsoidal variability is easily seen. Because of noticeable decrease of brightness in V the data have been divided into two subsets. First subset contains points from the left part of data (JD 2444500–2446500) and second from the right part of it (JD 2448000–2449500) – see Fig. 1. The both subsets of data in V and the set of J data were phased and are shown in Figs 2 and 3, respectively. The ephemeris of Lines et al. (1988):

$$\text{Min I} = \text{JD } 2431931.05 + 227.67\ E, \tag{1}$$

was used to phase the data. The initial epoch is a time of spectroscopic conjunction with the M giant in front.

3.2 Admissible parameters of the T CrB binary system

Since T CrB is noneclipsing system, the ellipsoidal light variation and the spectroscopic orbital solution for the M giant

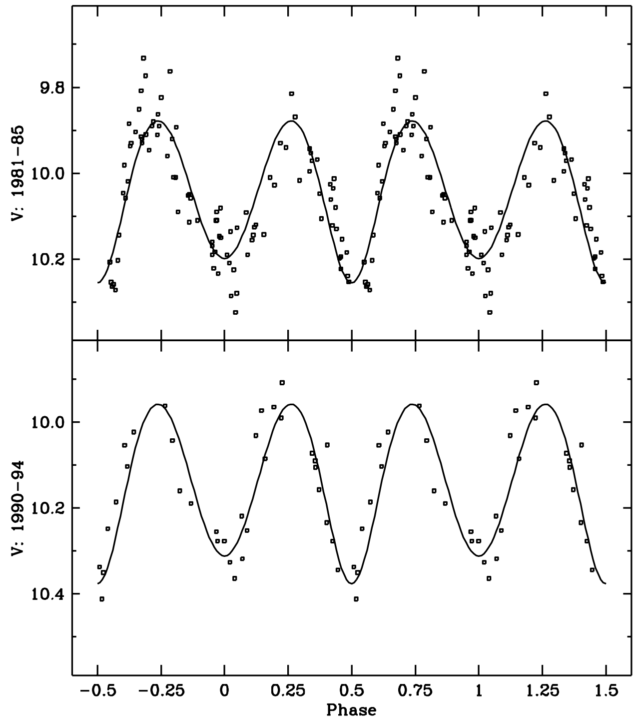

Figure 2. Synthetic V light curves for the model with $q = 0.6, i = 60^\circ, \alpha = 0.95$ and $e = 0.0$.

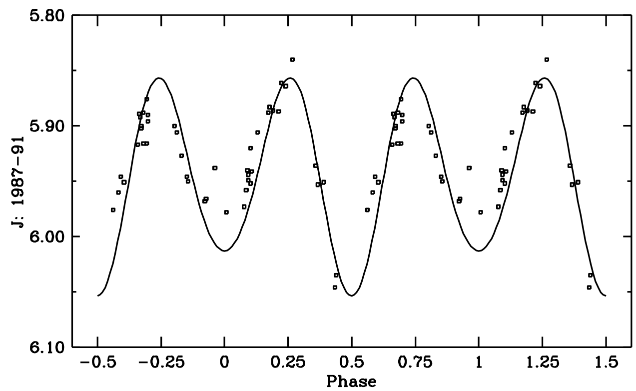

Figure 3. Synthetic J light curve for the model with $q = 0.6, i = 60^\circ, \alpha = 0.32$ and $e = 0.0$.

are not sufficient to fully constrain the system parameters (Morris 1985; Hall 1990). We need additional constraints.

As demonstrated by SCG, the quiescent IUE observations combined with X-ray detections, flickering, and the outburst behavior of T CrB point out toward a massive white dwarf as the hot component in the system. The only problem met was the hot component's radial velocity measurements by Kraft (1958), which resulted in its mass above the Chandrasekhar limit. To solve this problem, SCG just stretched the probable errors of Kraft's measurements to show that the massive white dwarf can be compatible with his solution. Basing on the arguments given by SCG (recalled here in Sec. 1), and the fact that recent studies have shown that the Balmer H I emission lines in T CrB do not follow the hot component (see also Sec. 1), we reject the orbital solution for the hot component, and instead we as-

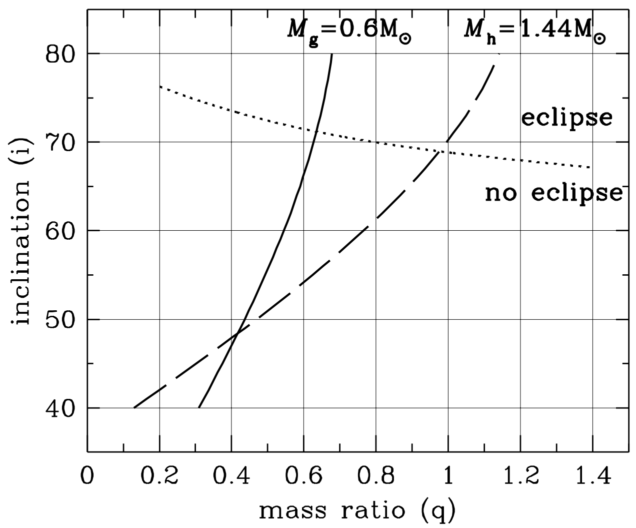

Figure 4. Parameter space diagram for T CrB. The permitted region is confined by the line of eclipses (dotted curve), and two constraints for the components' masses: $M_{\rm h} < 1.44{\rm M}_\odot$ (dashed curve) and $M_{\rm g} > 0.6{\rm M}_\odot$ (solid curve).

sume that its mass does not exceed the Chandrasekhar limit, $M_{\rm h} \lesssim 1.44{\rm M}_\odot$. We also assume that a reasonable limit to the red giant mass is $M_{\rm g} \gtrsim 0.6{\rm M}_\odot$, which ensures the secondary can evolve to giant dimensions during the lifetime of the Galaxy (e.g. Webbink 1988).

Fig. 4 presents i versus q diagram for T CrB. Using the mass function derived by KG

$$f(M) = M_{\rm h}\ \sin^3 i/(1+q)^2 = 0.30 \pm 0.01\ [{\rm M}_\odot] \qquad (2)$$

with $q = M_{\rm g}/M_{\rm h}$, we plotted the lines corresponding to $M_{\rm h} = 1.44{\rm M}_\odot$ with T CrB being to the left, and $M_{\rm g} = 0.6{\rm M}_\odot$ – with T CrB to the right, respectively. The line of eclipses, with T CrB being below it, further constraints the possible values of q and i.

Figure 2 shows that any reasonable mass ratio is below 1.0, which implies that the red giant is the less massive component of T CrB!

The low mass ratio is also in better agreement with the relatively low rotational velocity, $V_{\rm rot} \sin i \lesssim 10$ km/s, reported by KG. Since the giant cannot rotate faster than synchronously with the orbit, the rotational velocity provides the lower limit for q. KG estimated $q_{\rm min} = 0.4$. In T CrB, where ellipsoidal light variations demonstrate the importance of tidal effects, the giant's rotation should be synchronized with the orbital motion. Zahn (1977) derived synchronization and circularization time scales for convective stars in good agreement with the observations of binary systems. Using his Eqs. (61) and (62) we estimate $t_{\rm synchr} \sim 300$ yr, and $t_{\rm circ} \sim 3000$ yr, respectively, for $q \lesssim 1$. KG noticed that the giant would be not synchronized if it evolved up to the giant branch on a rapid timescale ($\lesssim t_{\rm synchr}$). It does not however seem very plausible. They also remarked that limb darkening and radiation from the hot component can reduce the observed $V_{\rm rot} \sin i$. Both effects can be important in the case of T CrB. The radial velocity measurements used by KG come from the period 1982-85, when the hot component was relatively bright, and its contribution to the light the 5200 Å bandpass was more than 10 % as indicated by flickering in V and B light observed in 1983 by Lines et al. (1988). We believe that the combined effect of additional hot component radiation and limb darkening can easily reduce the observed $V_{\rm rot} \sin i$ by 15-30 % with respect to the true value, and raise the mass ratio to $q \sim 0.5-0.6$. It is however unlikely, to increase by that means $V_{\rm rot} \sin i$ by a factor of ~ 2, and make it compatible with $q = 1.3$.

3.3 Light curve synthesis

Synthetic light curves have been computed using Wilson–Devinney code (Wilson 1990, 1992) for the admitted range of the mass ratio, $q = M_{\rm g}/M_{\rm h}$, and the orbital inclination, i (see Figure 2). Models were calculated for semi–detached configuration with the hot component very small as compared to the Roche lobe filling M giant.

Linear limb–darkening law has been assumed, and the $x^V = 0.95$, $x^R = 0.8$, $x^I = 0.6$ and $x^J = 0.5$ coefficients have been adopted in the V ($\lambda_{\rm eff} = 5500$Å), R ($\lambda_{\rm eff} = 7000$Å), I ($\lambda_{\rm eff} = 8800$Å) and J ($\lambda_{\rm eff} = 12500$Å), respectively. These coefficients have been interpolated from the tables of Van Hamme (1993), for the temperature $T_{\rm eff}$(M4III) = 3560 K (Ridgeway et al. 1980). The gravity–darkening exponent, α, defined through dependence of luminosity on local surface gravity, $L \sim g^\alpha$, has been taken as free parameter so long as $0.32 \leq \alpha \leq 1.0$, the theoretical values for stars with convective (Lucy 1967) and radiative envelopes (Von Zeipel 1924a,b,c), respectively. The black body approximation for wavelength dependence has been assumed in all our computations.

The IUE and optical spectrophotometry (SGC, WLTO, KG) suggests the hot component contributes very little to the total light of system beyond ~ 5000Å, to become practically invisible in the infrared (SCG, WLTO, KG). We have thus attributed all light in J passband to the red giant. The observed values of the $B-V$, and $U-B$ colors (Fig. 1) indicate very low contribution of the hot component to the U light, and none observable contribution to the B and V light in the period 1990-94. The optical faintness of the hot component at that epoch is also suggested by the appearance of the optical spectrum – the continuum and absorption features of the M4 giant with very faint H I Balmer emissions, and the lack of any flickering variability (Dobrzycka, Kenyon & Milone 1996). The presence of flickering (Lines et al. 1988) and emission lines in the optical spectrum (KG), as well as $B-V$ and $U-B$ colors observed in 1981–85 suggests some hot component contribution to the V light at that period. Comparing the average V magnitudes for T CrB in these two periods, and assuming that the contribution of the hot component to the total V light was negligible in 1991–94, we estimate that this contribution in period 1981-85 was about 10 per cent. We have also neglected the hot component contribution to the J light for the whole analyzed period. Based on the IUE data from 1979–90 SCG demonstrated that the hot component luminosity never exceeded 100 L$_\odot$, thus any reflection effect produced by the hot component in the red giant is negligibly small for the whole period.

The ellipsoidal variation has much larger amplitude in V than in J band: $\Delta V \sim 0.4$, and $\Delta J \sim 0.15$, respectively. So different amplitudes cannot be reproduced by our model light curves for any set of parameters. In particular, the large amplitude in V light requires generally large values of the

gravity–darkening exponent, $\alpha \sim 1$ for any binary parameters, while the much lower J amplitude is consistent with $\alpha \sim 0.32$ for any reasonable q and i. The need of very high value of $\alpha \gtrsim 1$ to account for the observed visual amplitude was already reported by Bailey (1975), who adopted the Kraft mass ratio, $q = 1.4$, and the highest possible inclination $i = 68°$ (for which the system is still not eclipsing).

In this situation, we have analyzed the V and J light curves separately. The grid of V and J light curves was generated for q and i in the range suggested by Figure 2, and α as a free parameter. The synthetic light curves fit the observations fairly well in the range $0.4 < q < 0.8$ and $55° < i < 65°$, with $\alpha \sim 1$ for the V light curve and ~ 0.32 for the J light curve. Figs 2, and Fig. 3 present examples of our solutions for V and J, respectively. Identical light curves are obtained for the other admitted values of q and i. Below we use the middle values, $q = 0.6$ and $i = 60°$, with the errors defined by their extremes. These errors propagate onto our results (see Table 2). Our solutions are presented in Figs 2 and 3.

For mass ratios $q < 1$ adopted in our study the red giant is more tidally distorted then in the models with $q \geq 1.0$, which implies generally larger amplitudes of ellipsoidal variation, and allows the gravity darkening exponent α to be smaller in better agreement with the theory. Unfortunately, the inconsistency between the V and J amplitudes of our synthetic light curves remains. In particular, this inconsistency cannot be explained by poor quality of the J light curve. Using the values of parameters derived from the V light curves we estimate the amplitude of the ellipsoidal variation, $\Delta J_{\rm I} = 0.20$, and $\Delta J_{\rm II} = 0.29$, for the primary and secondary minimum, respectively. These values exceed the observed amplitudes by ~ 0.1, which is much more than accuracy of the observations in the J band. According to Yudin & Munari (1993) the J data have internal accuracy better than 0.02 mag, and the data from different orbital cycles fit the same light curve with similar accuracy.

To find out why we get so different values of the gravity darkening coefficient for different light curves, we have calculated the amplitudes in the R and I bands for $q = 0.6$, $i = 60°$, and two values of α: 0.32, and 1, respectively. Our calculated $\Delta I_{\rm I} = 0.17$, $\Delta I_{\rm II} = 0.24$ ($\alpha = 0.32$), well agree with the observed amplitude $\Delta i \approx 0.17$ reported by Lines et al. (1988), and $\Delta I \approx 0.2$ estimated from the light curve published by Mikołajewski et al. (1997), while the observed amplitudes in the red band, $\Delta r \approx 0.3$ (Lines et al. 1988), and $\Delta R \approx 0.33$ (Mikołajewski et al. 1997) are in agreement with the model values, $\Delta R_{\rm I} = 0.29$, $\Delta R_{\rm II} = 0.36$, for $\alpha = 1$. Thus we meet again the problem that the ellipsoidal variability in I light can be reproduced with the lower (convective) value of $\alpha = 0.32$, while the observed amplitude in R band requires high (radiative) values of $\alpha \sim 1$.

We believe the high values of α suggested by visual and red amplitudes of the ellipsoidal variation result from the black body approximation for wavelength dependence in the Wilson–Devinney code. This assumption is probably not valid in the case of M type stars with strong TiO bands in the optical and red part of spectrum. The TiO bands are very sensitive to even small changes in the effective temperatures, and so can strongly affect the broadband V and R magnitudes giving rise to much larger light changes than calculated under black body assumption in the WD code.

Table 2. Adopted parameters for T CrB.

Parameter	Value
Mass ratio, q	0.6 ± 0.2
Orbital inclination, i	$60° \pm 5°$
Gravity–darkening, α	0.32
Hot component mass, $M_{\rm h}$	$1.2 \pm 0.2 M_\odot$
M giant mass, $M_{\rm g}$	$0.7 \pm 0.2 M_\odot$
Orbital separation, a	0.9 ± 0.1 au ($194 \pm 22 R_\odot$)
M giant radius, $R_{\rm g}$	0.34 ± 0.02 au ($66 \pm 11 R_\odot$)
M giant temperature, $T_{\rm eff}$	3560 K
M giant luminosity, $L_{\rm g}$	$620 \pm 120 L_\odot$
Distance, d	960 ± 150 pc

For $q = 0.6$, $i = 60°$, and $\alpha = 0.32$, we estimate the mean gravity ratio $g_{\rm minI}/g_{\rm max} \sim 0.84$ (where $g_{\rm minI}$ and $g_{\rm max}$ have been averaged over the M giant's surface visible at minimum and maximum, respectively), and accordingly averaged effective temperatures, $T_{\rm minI} \sim 3500$ K, and $T_{\rm max} \sim 3560$ K, respectively. Adopting $(V - J)_{\rm minI} = 4.45$, and $(V - J)_{\rm max} = 4.19$ (M4.3 III; 3500 K, and M4 III; 3550 K, respectively; Straizys 1992), the J amplitude, $\Delta J_{\rm I} = 0.15$, implies $\Delta V_{\rm I} = 0.41$. The later value is very close to the observed V amplitude, while the V amplitude calculated in the WD code for the same parameter set, $\Delta V_{\rm I} = 0.21$, is by a factor of 2 lower than the observed one!

There is a moral in that to analyze the ellipsoidal variability in symbiotic binary systems with M giant components, either one should base the analysis on the infrared light curves (where the black body approximation for wavelength dependence is acceptable) or, if only the optical data are available, model M giant atmospheres should be used for the wavelength dependence.

Table 2 summarize the adopted parameters for T CrB. Assuming that the M giant fills its tidal lobe, we have estimated its radius and luminosity, and the distance to T CrB.

3.4 Spurious eccentricity induced by tidal distortion

So far our analysis has been made under assumption of circular orbit of the T CrB system. KG however noted that an eccentric orbit with $e = 0.012 \pm 0.005$ slightly improves the fit to the radial velocity data. They interpreted that eccentricity as resulting from the contribution of the axial rotation of the tidally deformed giant, which has a nonuniform surface brightness, to its observed radial velocity. The effect was studied in detail by Sterne (1941), who demonstrated that it gives rise to a spurious eccentricity, $e_{\rm t}$, in the orbital solution given by

$$e_{\rm t} = 1.5\ q^{-1}(1+q)(R_{\rm g}/a)^4 \sin i\ f(x, \beta_2), \qquad (3)$$

where $R_{\rm g}$ is the giant's radius, a is the orbital separation, and f is the function of the selective gravity–darkening coefficient β_2, and the limb–darkening coefficient x:

$$f(x, \beta_2) = \frac{8\beta_2 - 3x\beta_2 - 5x}{20(3-x)}. \qquad (4)$$

The coefficient β_2 can be estimated from

$$\beta_2 = \alpha \frac{1.43879 \times 10^8/\lambda T}{1 - \exp(-1.43879 \times 10^8/\lambda T)} \qquad (5)$$

(the gray body approximation). Sterne (1941) has also shown that for a circular orbit the spurious longitude of periastron $\omega_{\rm t} = 90^{\circ}$ or 270° according to whether f is positive or negative. KG derived $\omega = 80^{\circ} \pm 6^{\circ}$, which suggests the tidal distortion is the dominant source of the eccentricity they found. KG has also proposed to use that eccentricity as an indirect measure of the mass ratio. Unfortunately, their Eq. (5), as well as their Fig. 5, used for that purpose contain errors, and their value of $q = 1.3$ is wrong.

Using our expression for $e_{\rm t}$, we find very weak dependence of $q_{\rm min}$ (for a lobe–filling giant) on the spurious eccentricity $e_{\rm t}$. In particular, the term $q^{-1}(1+q)(R_{\rm g}/a)^4$ changes from 0.032 to 0.056 for q increasing from 0.5 to 2.0. Adopting reasonable values of $x \sim 0.9$, and $\beta_2 \sim 2.3$ (the value corresponding to $\lambda \sim 5200\AA$, $T = 3560$K, and $\alpha = 0.32$), $q = 0.6$ and $i = 60^{\circ}$, we estimate $f(0.9, 2.3) = 0.18$, and $e_{\rm t} = 0.009 \pm 0.002$ which is very close to $e = 0.012 \pm 0.005$ derived by KG. Although this is a very rough estimate due to crudity of the adopted values upon which it depends, it strongly points to tidal effects as the source of the eccentricity reported by KG. Moreover, this results also provides significant support for the low value of the gravity–darkening exponent, $\alpha = 0.32$. Higher α's result in higher values of f, and so $e_{\rm t}$. For example, $\alpha = 1$ will increase our $e_{\rm t}$ by a factor of 4.

3.5 Asymmetry in the orbital light curve

In addition to erratic and secular variations caused by the hot component, the orbital V light curves of T CrB (Fig. 3) show some systematic asymmetry: the ingress to the primary minimum is slightly longer than the egress, and in the 1981–1985 period the maximum following the primary minimum (Max I; $\phi \sim 0.25$) seems to be lower than the second maximum (Max II; $\phi \sim 0.75$). It is hard to say whether this asymmetry is also present in the J and the 1990–94 V light curves because there is not enough data points.

There are many possible causes of asymmetry in orbital light curves: noncircular orbit, hot or cool spots on the cool giant, asymmetry in the hot component.

3.5.1 Eccentric orbit

To check whether an eccentric orbit can account for the asymmetric shape of the V light curve, we have calculated synthetic light curves for fixed values of $q = 0.6$, $i = 60^{\circ}$, and $\alpha = 0.95$ (our best solution for V light curves from Sec. 3.3), with e and ω as free parameters. The model with $e = 0.05$ and $\omega = 120^{\circ}$ (measured from the ascending node as in Sterne (1941) and KG) reproduces reasonably well the distorted shape of the primary minimum and the difference in heights of maxima. The required value of e exceeds by more than 3σ the eccentricity $e = 0.012 \pm 0.005$ found by KG. The comparison of this result with the eccentric orbit derived by KG is however not so straightforward. If the orbit is indeed eccentric, one should expect the spurious tidal eccentricity to combine with the real e, to yield a resultant (which is the spectroscopically measured one) which can be either larger or smaller than the real e. So, the radial velocities should be corrected for the tidal effects before solving for the spectroscopic orbital elements. As we have demonstrated in Sec. 3.4, the spectroscopic eccentricity found by KG can be fully accounted by the tidal distortion of the M giant. Thus there is no evidence for any real eccentricity in the radial velocity data.

3.5.2 Asynchronous rotation and reflection

Leibowitz et al. (1996) recently analyzed visual magnitude estimates of T CrB spanning a 40-year period, and found that the photometric minima are systematically delayed (the primary minimum by $4\overset{\rm d}{.}7$, and the secondary by $1\overset{\rm d}{.}7$, respectively) with respect to the times of spectroscopic conjunctions given by KG. They argued that this effect is due to asynchronous rotation of the M giant. If the giant rotates slower than synchronously the tidal distortion wave on its surface is lagging behind the interbinary radius vector (Lecar, Wheeler & McKee 1976), and the ellipsoidal light minima will be delayed with respect to spectroscopic conjunctions, but there will be no difference in the delay times of the two minima. Leibowitz et al. proposed that the difference in the lags of the two minima, and the general asymmetry in the orbital light curve is caused by combined effects of the giant's asynchronous rotation and the illumination of the giant's atmosphere by the hot companion. Their model however faces serious problems when confronted with the observational data.

First of all, there is no observational evidence for significant reflection effect in T CrB. The hot component is not very luminous (SCG, and Sec. 3.3), while the TiO band depths do not show any measurable phase dependence (Kenyon & Fernandez–Castro 1987) indicating that any temperature contrast on the giant's surface, $\Delta T_{\rm eff} \lesssim 50$K. Moreover, even if there is any reflection effect, our exemplary synthetic light curves show the primary maximum ($\phi = 0.25$) to be higher than the secondary ($\phi = 0.75$), and the interval between the primary and secondary minima should be larger than 0.5 P, contrary to what we do observe in T CrB.

Finally, as we argue in Sec. 3.2, for the mass ratio resulting from our analysis, much lower than any previous estimates, the low rotation velocity reported by KG does not necessarily imply that the rotation of the giant is not synchronized with the orbital rotation.

3.5.3 Accretion disk with asymmetric brightness distribution

Analysis of the slope and intensity of the IUE continuum led SCG to the conclusion, that the bulk of the UV luminosity of T CrB originates from a nonstationary accretion disk around a white dwarf. They also remarked that though the disk luminosity contributes mostly to the satellite UV, there should be also some disk contribution (a few $L_{\odot}$) to the optical luminosity of T CrB. This contribution is clearly visible in the U, B and V light in 1981–85, while practically absent in 1990–94. Comparison of the average U, B and V magnitudes in these two periods indicates the optical luminosity of the disk was $L_{UBV} \gtrsim 7L_{\odot}$ in 1981–85, in agreement with the value predicted by SCG. The data in Table 1 of SCG also indicate that in 1989 the average UV luminosity of T CrB dropped by a factor of $\sim 3-4$ with respect to the average UV luminosity in 1981–85, which explains the

absence of the additional hot source in the 1990–94 light curves. The available data suggest the asymmetry is best visible in the 1981–85 V light curve, thus an interpretation in terms of asymmetric brightness distribution in the accretion disk seems plausible.

Such interpretation is also supported by observations of accretion disks in binary systems. Quiescent light curves of dwarf novae show characteristic orbital hump, observed during approximately one–half of the cycle, due to the presence of the hot spot (e.g. Warner 1995, and references therein). Studies of the disk–accreting Algol–type systems show that the trailing side of the disk (where the gas stream adds to the disk) is brighter, while the leading edge is usually more extended (Batten 1989, and references therein).

Applying the results of Lubov & Shu (1975) to T CrB we have estimated the radius of the disk of $\sim 0.1a(20\mathrm{R}_\odot)$, and the angle between the radius vector of the accretion stream–disk impact and the interbinary radius vector of $\sim 70°$. So if there is any bright spot in that region, its best visibility corresponds to the orbital phase ~ 0.8, and it can at least qualitatively account for the difference in heights of the photometric maxima observed in T CrB. Such bright stream–disk impact region can be also responsible for the erratic light changes and the flickering variability, which are apparently correlated with the average UV fluxes, and the brightness of the additional optical continuum source. A detailed modeling of that effect is however very complicated, and beyond the scope of this paper.

4 SUMMARY AND CONCLUDING REMARKS

Based on constraints from the orbital solution for the M giant and the amplitude of ellipsoidal light changes, and imposing additional limits on the components masses ($M_\mathrm{g} \gtrsim 0.6\mathrm{M}_\odot$; $M_\mathrm{h} \lesssim 1.44\mathrm{M}_\odot$), we narrow down the range of permissible values for the T CrB system parameters (Table 2). Contrary to all previous studies, our analysis shows that the mass ratio of T CrB $q \equiv M_\mathrm{g}/M_\mathrm{h} \approx 0.6$ indicating a low mass binary system, with the stellar masses $M_\mathrm{g} \sim 0.7\mathrm{M}_\odot$, and $M_\mathrm{h} \sim 1.2\mathrm{M}_\odot$. Our analysis also suggests that the binary orbit is circular, and the giant seems to rotate synchronously with the orbit, in agreement with the theoretical predictions for a binary with a Roche lobe–filling M giant (Zahn 1977). Our result for the masses of the system components solves practically all basic controversies about the nature of the hot component and the physical causes of its eruptions. The thermonuclear runaway in a massive white dwarf as proposed by SCG is fully compatible with *all* observational facts.

The mass ratio of T CrB, $q \sim 0.6$, is also in better agreement with the theory of binary evolution than is the previously accepted $q \sim 1.3$. Paczyński (1965b) showed that semidetached binaries with red giant primaries can be dynamically unstable, and recent publications demonstrate that large mass ratios $q \gtrsim 0.8$ are always unstable (Webbink 1988; Pastetter & Ritter 1989). Except for the two nova–like eruptions in 1866 and 1946, T CrB does not manifest any dramatic activity that would indicate dynamically unstable mass transfer. The erratic activity discussed in Sec. 3.1 is at similar level as in RS Oph, a sister recurrent nova system with a massive $\sim 1.2\mathrm{M}_\odot$ white dwarf, and a low mass $\sim 0.5\mathrm{M}_\odot$ M giant companion (Shore et al. 1996; Dobrzycka & Kenyon 1994; Dobrzycka et al. 1996b). SCG estimate $\dot{M}_{acc} \sim 2.5\times10^{-8}\mathrm{M}_\odot\mathrm{yr}^{-1}$ for T CrB, similar to $\dot{M}$ derived by Dobrzycka et al. for RS Oph, which is several orders of magnitude lower than $\dot{M} \sim 10^{-2} - 10^{-3}\mathrm{M}_\odot\mathrm{yr}^{-1}$ expected in the state of runaway mass transfer (Webbink 1988). Moreover, according to the theory of symbiotic binary formation and evolution under suitable conditions low–mass systems containing massive white dwarfs, although relatively rare, may survive as symbiotic stars for a very long time in a Roche lobe–filling state (Webbink 1988). T CrB is undoubtedly one of such systems.

We have also discussed possible causes for the asymmetry in the visual light curve of T CrB. Although we cannot propose any definitive interpretation, the most promising is asymmetric brightness distribution in the accretion disk surrounding the white dwarf. To make significant progress we need not only better observations, especially in the infrared, but also improvements in the light curve analysis and spectroscopic modeling, including for instance implementation of M giant atmospheres option, or line profile simulations to model both velocity field variation across the stellar disk, and the weighted effects of brightness asymmetries.

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REFERENCES

Anupama G.C., 1997, in Mikołajewska J., ed., Physical Processes in Symbiotic Binaries and Related Systems, Copernicus Foundation for Polish Astronomy, Warsaw, p.117
Bailey J., 1975, J. Brit. Astron. Assoc., 85, 217
Batten A.H., ed., 1989, Algols, Kluwer
Dobrzycka D., Kenyon S.J., 1994, AJ, 108, 2259
Dobrzycka D., Kenyon S.J., Milone A.A.E., 1996a, AJ, 111, 414
Dobrzycka D., Kenyon S.J., Proga D., Mikołajewska J., Wade R.A., 1996b, AJ, 111, 2090
Canizzo, J.K., Kenyon, S.J., 1992, ApJ, 386, L17
Hall, D.S., 1990, AJ, 100, 554
Hric L., Urban Z., Niarchos P., Petrik K., 1997, in Mikołajewska J., ed., Physical Processes in Symbiotic Binaries and Related Systems, Copernicus Foundation for Polish Astronomy, Warsaw, p.175
Hric L. et al., 1991, Contrib.Astron.Obs. Skalnate Pleso, 21, 303
Hric L. et al., 1993, Contrib.Astron.Obs. Skalnate Pleso, 23, 73
Hric L. et al., 1994, Contrib.Astron.Obs. Skalnate Pleso, 24, 31
Johnson H.L., 1966, ARA&A, 4, 193
Kenyon S.J., 1986, The Symbiotic Stars, Cambridge Univ. Press
Kenyon S.J., 1988, AJ, 96, 337
Kenyon S.J., Fernandez–Castro T., 1987, AJ, 93, 938
Kenyon S.J., Garcia M.R., 1986, AJ, 91, 125 (KG)
Kraft R.P., 1958, ApJ, 127, 620
Leibowitz E.M., Ofek E.O., Mattei J.A., 1996, submitted to MNRAS
Lecar M., Wheeler J.C., McKee C.F., 1976, ApJ, 205, 556
Lubov S.H., Shu F.H., 1975, ApJ, 198, 383
Lines H.C., Lines R.D., McFaul T.G., 1988, AJ, 95, 1505
Lucy L.B., 1967, Zs.f.Ap., 65, 89
Mikołajewski M., Tomov T., Kolev D., 1997, Inf. Bull. Variable Stars No. 4428

Morris, S.L., 1985, ApJ, 295, 143
Paczyński B., 1965a, Acta Astron., 15, 197
Paczyński B., 1965b, Acta Astron., 15, 89
Pastetter L., Ritter H., 1989, A&A, 214, 186
Raikova D., Antov A., 1986, Inf. Bull. Variable Stars No. 2960
Ridgway S.T., Joyce R.R., White N.M., Wing R.F., 1980, ApJ, 235, 126
Sanford R.F., 1949, ApJ, 109, 81
Selvelli P.L., Cassatella A., Gilmozzi R., 1992, ApJ, 393, 289 (SCG)
Shore S.N., Kenyon S.J., Starrfield S., Sonneborn G., 1996, ApJ, 456, 717
Skopal L. et al., 1992, Contrib. Astron. Obs. Skalnate Pleso, 22, 131
Skopal L. et al., 1995, Contrib. Astron. Obs. Skalnate Pleso, 25, 53
Sterne T.E., 1941, Proc. Natl. Acad. Sci, 27, 168
Straizys, V., 1992, Multicolor Stellar Photometry, Pachart Foundation, Tucson
Von Zeipel H., 1924a, MNRAS, 84, 665
Von Zeipel H., 1924b, MNRAS, 84, 684
Von Zeipel H., 1924c, MNRAS, 84, 707
Van Hamme W., 1993, AJ, 106, 2096
Warner B., 1995, Cataclysmic Variable Stars, Cambridge Univ. Press
Webbink R.F., 1988, in Mikołajewska J., Friedjung M., Kenyon S.J., Viotti R., eds., The Symbiotic Phenomenon, Kluwer, p. 311
Webbink R.F., Livio M., Truran J.W., Orio M., 1987, ApJ, 314, 653 (WLTO)
Wilson R.E., 1990, ApJ, 356, 615
Wilson R.E., 1992, Documentation of Eclipsing Binary Computer Model, Dept. of Astronomy, Univ. of Florida
Yudin B., Munari U., 1993, A&A, 270, 165
Zahn J.–P., 1977, A&A, 57, 383

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